Semiconductor detectors: from particle tracking to vision for the blind

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Glasgow detector group:

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Outline

Overview of Glasgow detector group activities

Particle tracking with 3D detectors

Silicon carbide as a radiation hard medium

CERN Medipix for X-ray imaging

Retinal prosthetic devices for repairing blindness

Glasgow detector group activities

Group structure:

5 Research Associates

7 PhD / MSc students

4 Technical support

2 Senior engineer / physicist

2 Academic

Skills within group:

Detector / semiconductor characterisation

Electronic circuit design and layout

Photo- & e-beam lithography

Device modelling / simulation

Project summary:

ATLAS, LHCb - PPARC Rolling Grant

3D detector - PPARC Opportunity, Framework V

Graded gap - PPARC ROPA

Widegap SiC, GaN - PPARC Detector R&D

Retinal - EPSRC Life Sciences

Beam profiler - Scottish Enterprise

MEDIPIX - Framework V

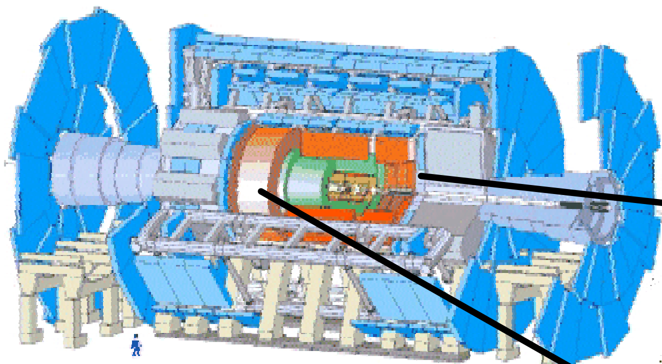
LAD, ERD - Case with RAL

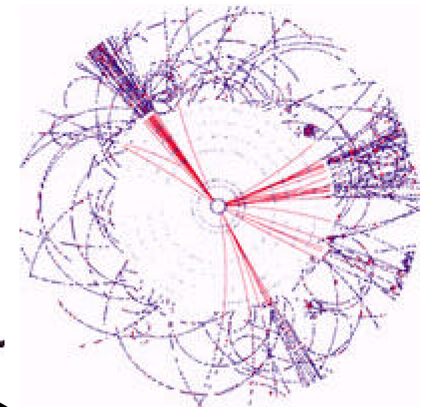
Lab-on-chip - with EE Bioelectronics

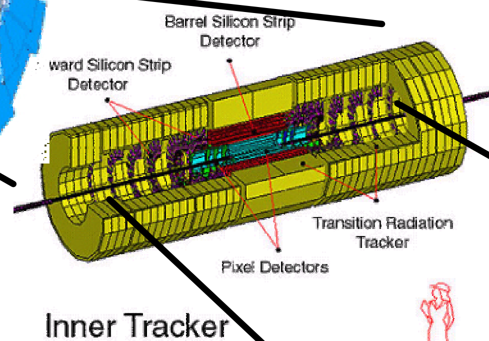
Radiation hard particle tracking I: 3D detectors

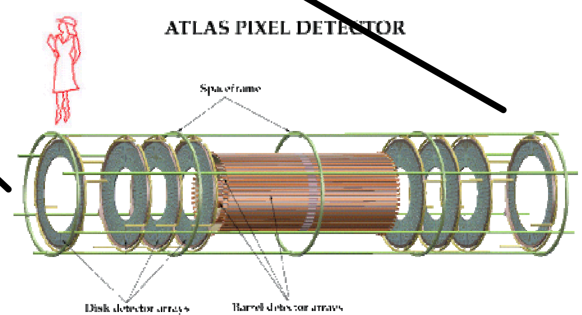
Tracking / vertexing detectors

Example of ATLAS at CERN Large Hadron Collider









<u>Semiconductor detectors</u>

compact, large signal, fast

Drawbacks: small size, radiation damage

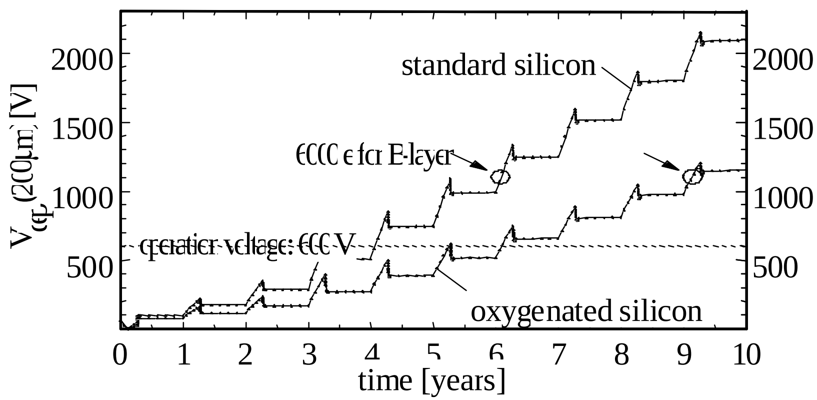
Radiation hard particle tracking

CERN RD50 collaboration – super-radiation hard detectors

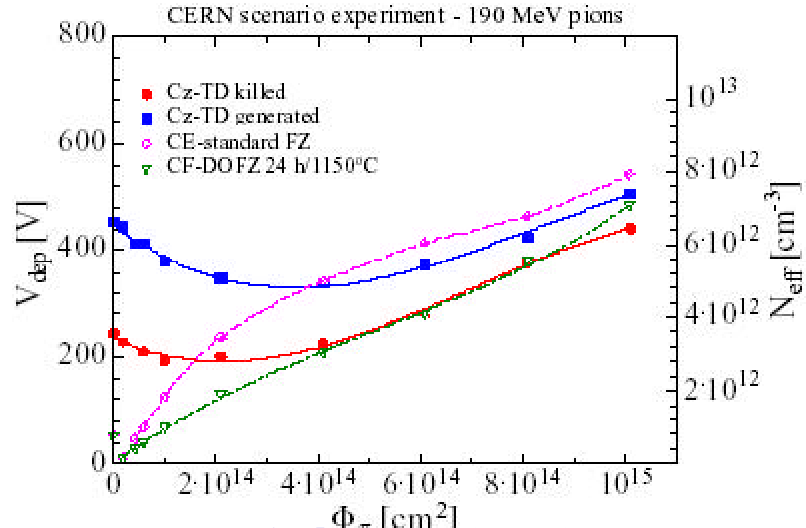
Development of super-radiation hard detectors:

→ Materials systems, eg oxygenated Si, SiC etc

→ Detector geometry,
  eg 3D, semi-3D, thin detectors



ATLAS B-layer (RD48 report)

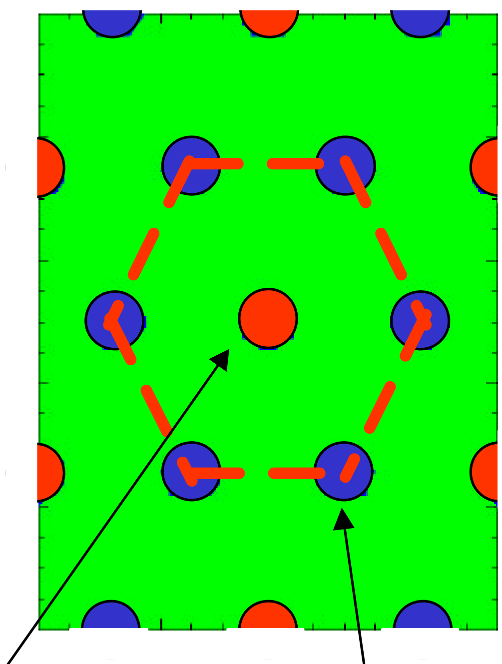


G Lindstroem (2002)

Planned upgrade to LCH, luminosity 10^{34} /cm^{2}s to 10^{35} /cm^{2}s, requires radiation hardness of trackers to fluences ~10^{16} n/cm^2

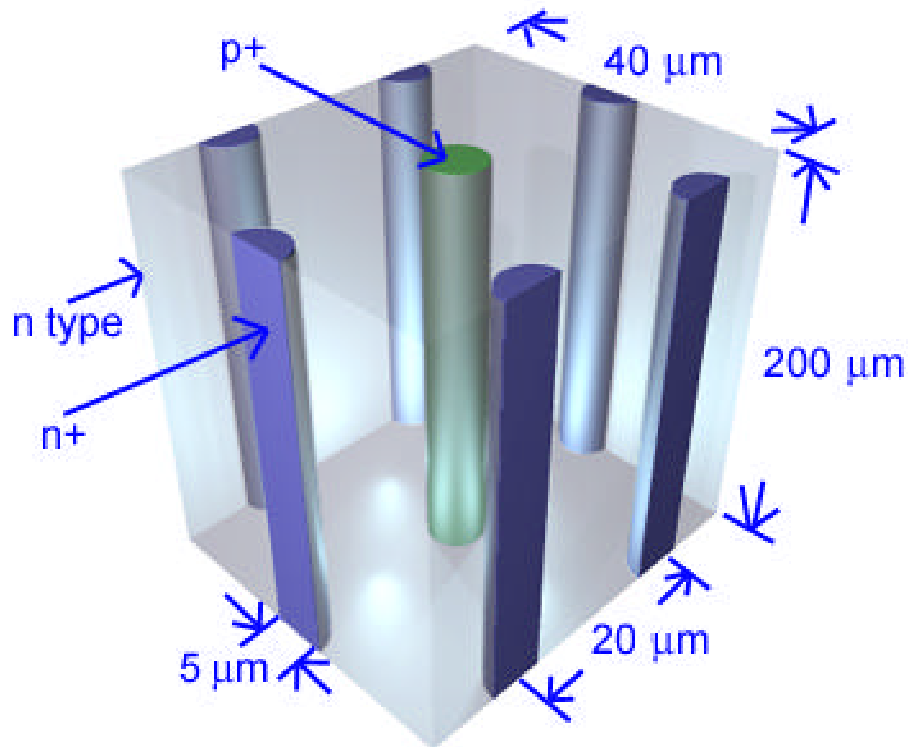
3D detectors

Electrodes perpendicular to wafer surface, bias field in wafer plane



Biased electrode

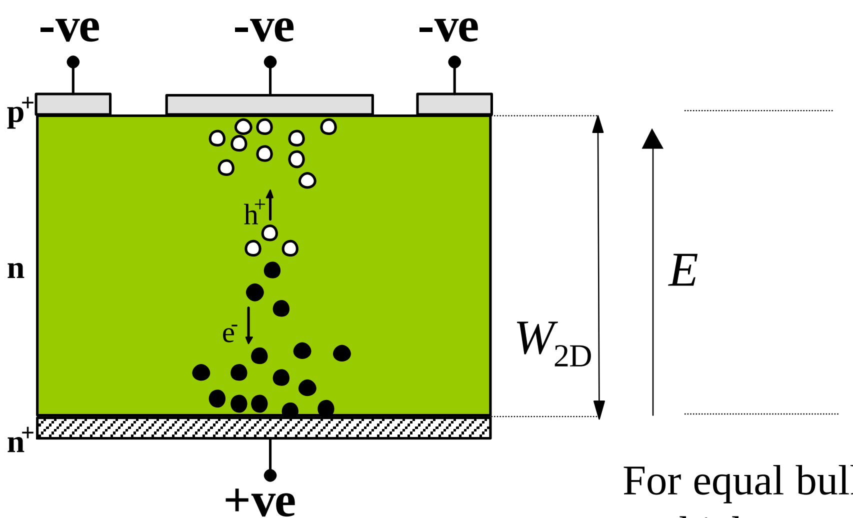
Grounded electrode



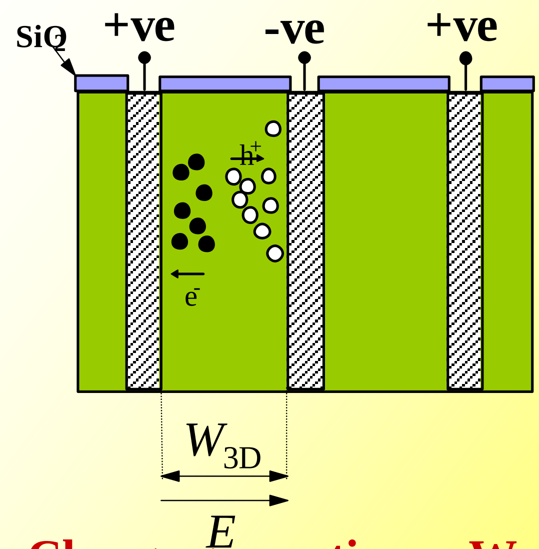
• **S Parker NIM A395, 328 (1997)**

Operation of 3D detector

Charge generation and collection directions decoupled



For equal bulk thickness
$W_{2D} >> W_{3D}$



Charge generation µ W_{2D}

Drift distance = W_{2D}

→ coupled

Charge generation µ W_{2D}

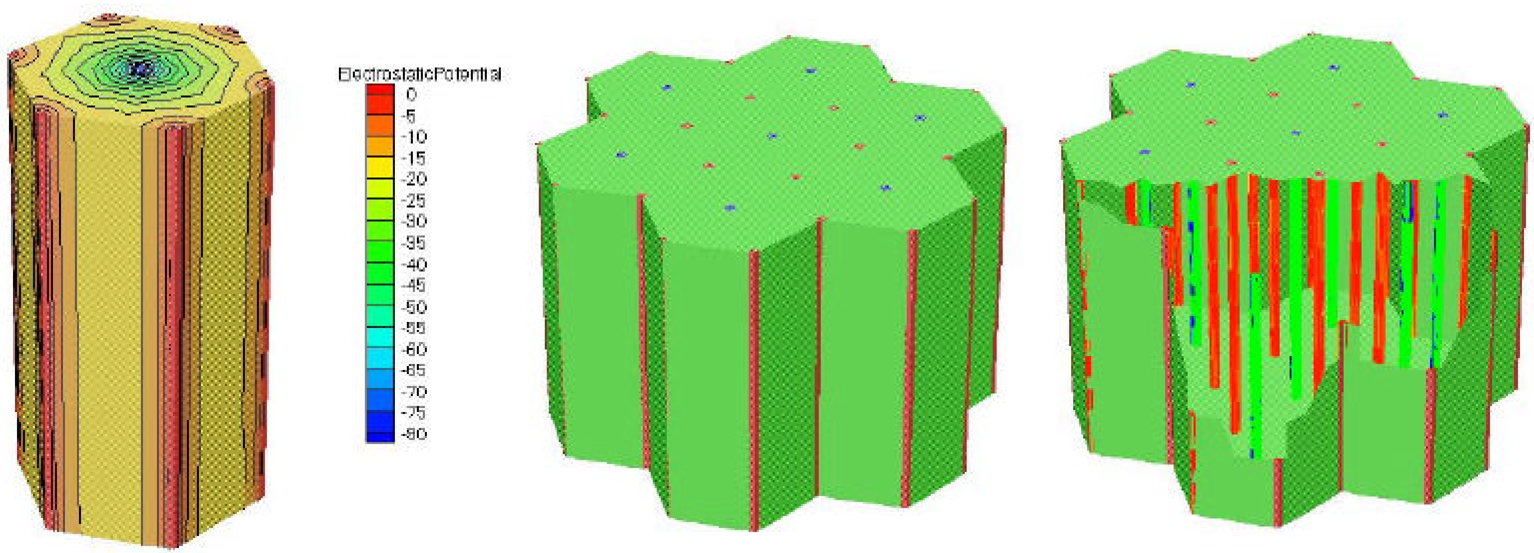
Drift distance = W_{3D}

→ <u>decoupled</u>

BUT increased complexity of fabrication

3D detector

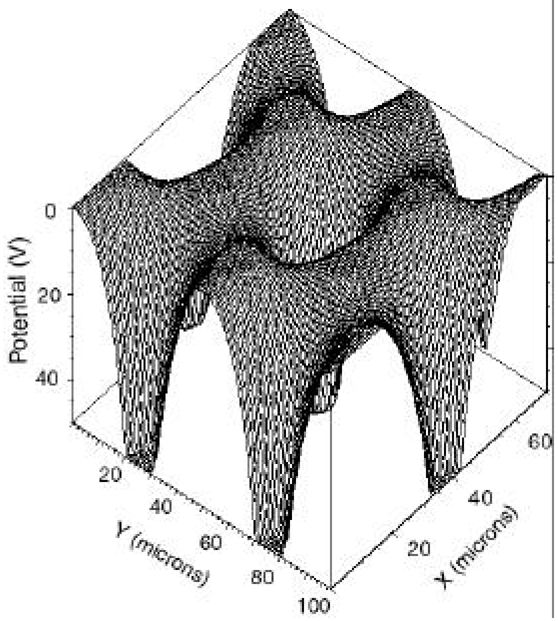
Hexagonal geometry gives radial field profile



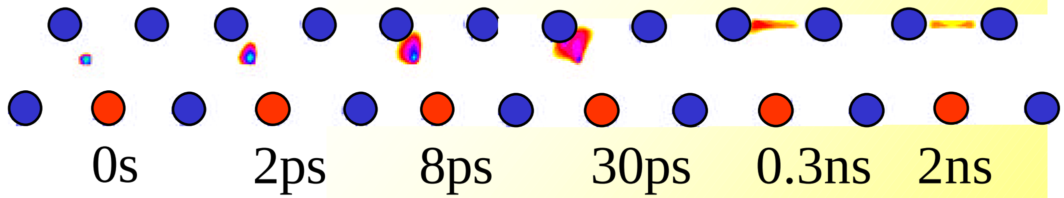
- **3-dimensional simulations using ISE**
- **Examine charge generation / collection (charge sharing) MIPs, X-rays, alphas**

3D detector – charge collection

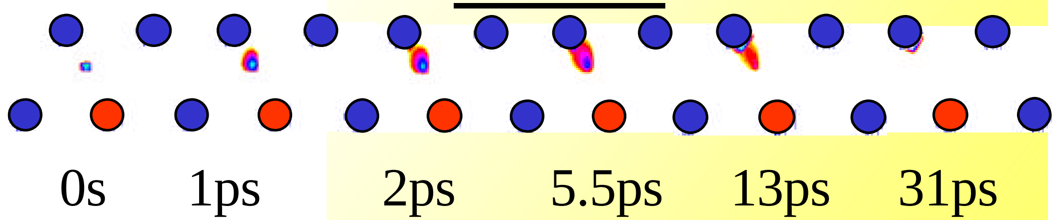
Medici (2D) simulations of charge collection and response times



50 V bias



75 V bias

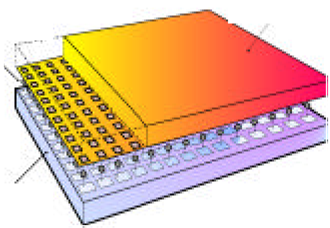


- Complete charge collection possible in <0.1 ns, compare ~10 ns for conventional

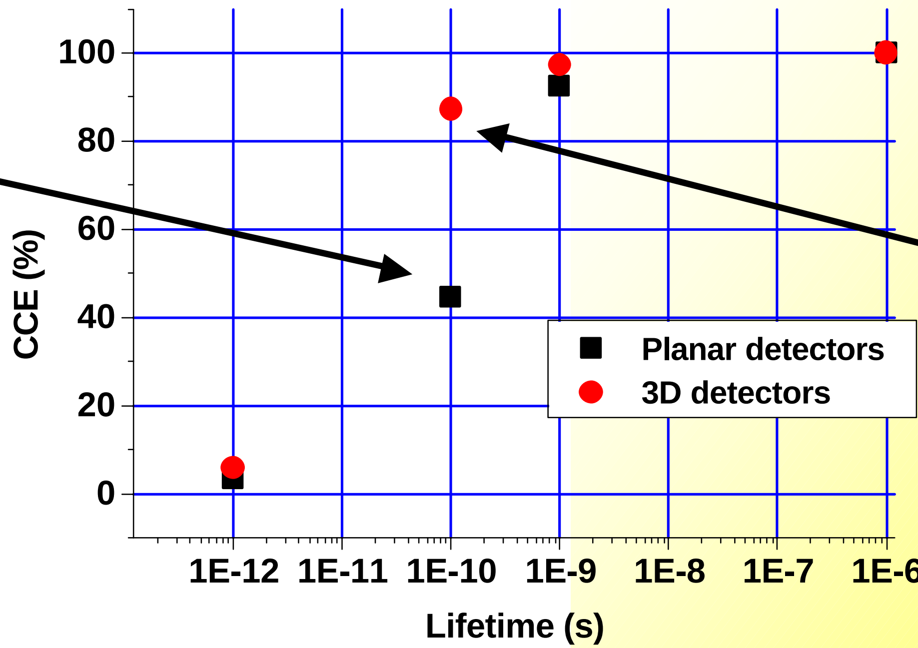
3D detector – radiation tolerance

Simulated CCE for uniform defect distribution (10^{14} cm^{-3}) but varying carrier recombination times from 1 μs down to 1 ps

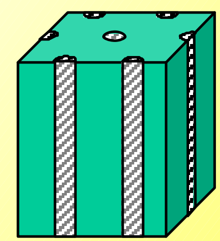
Conventional



600 V bias



3D detector



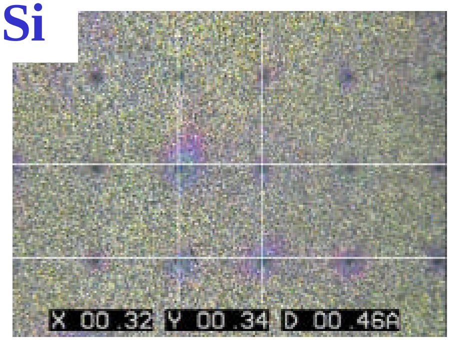
200 μm thick,
75 V bias

3D detector better than conventional for lifetimes 10^{-8} to 10^{-11} sec

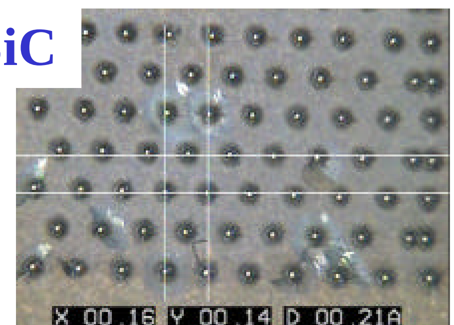
3D detector manufacture

Methods of 3D detector manufacture under investigation

Si



SiC



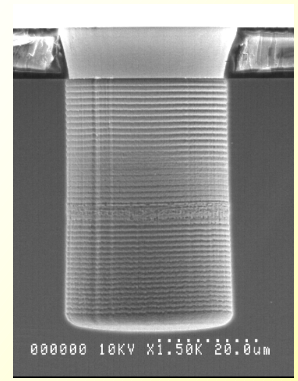
Laser ablation

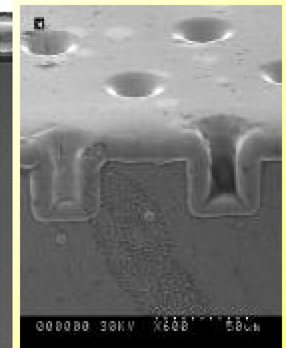
fs pulses are cleaner, any substrate

Three methods

Plasma etching

High control, time consuming





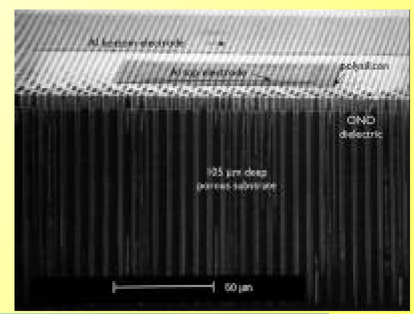
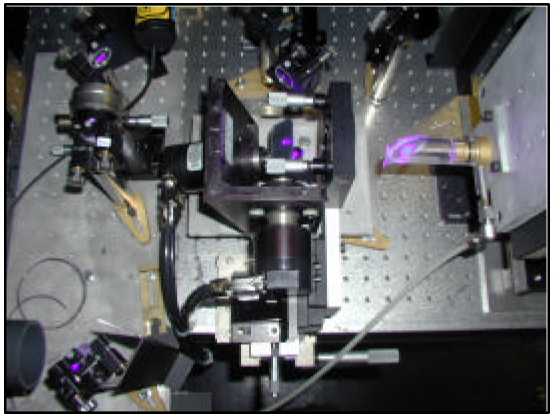


Photo-electrochemical etching

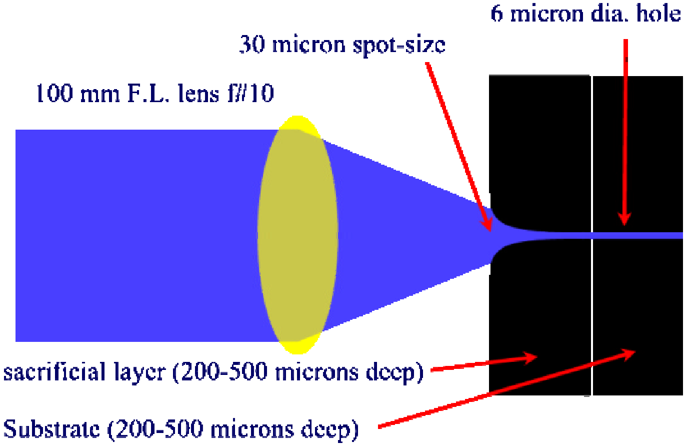
Fast, high aspect ratio, limited substrates?

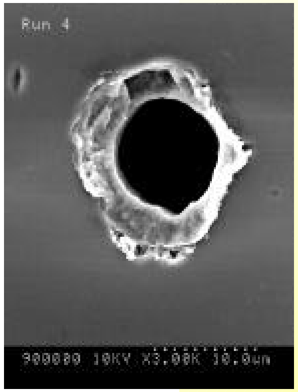
Femtosecond laser ablation of 3D pores

TOPS facility, Strathclyde University (Glasgow)

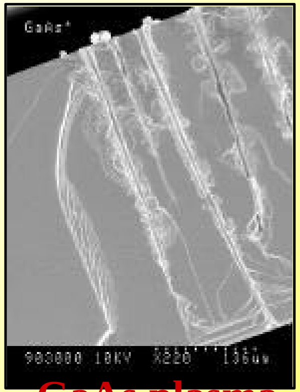


- Ti:Sapphire laser
- 3 mJ pulses with duration of 40 fs at 1 kHz repetition rate → 5 sec per hole
- 810 nm wavelength or 405 nm wavelength (frequency doubled)
- ~25:1 aspect ratio, material independent

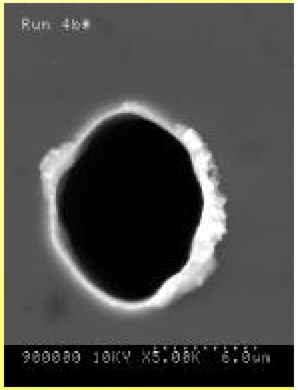




Si plume



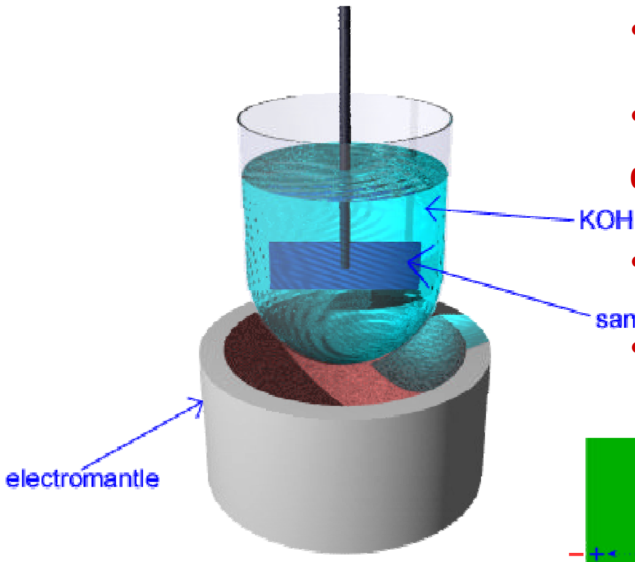
GaAs plasma effects



Si optimised

Photo-electrochemical (PEC) etching of 3D pores

Most promising of three methods → highest potential aspect ratios

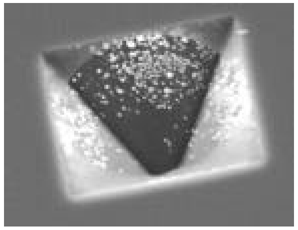


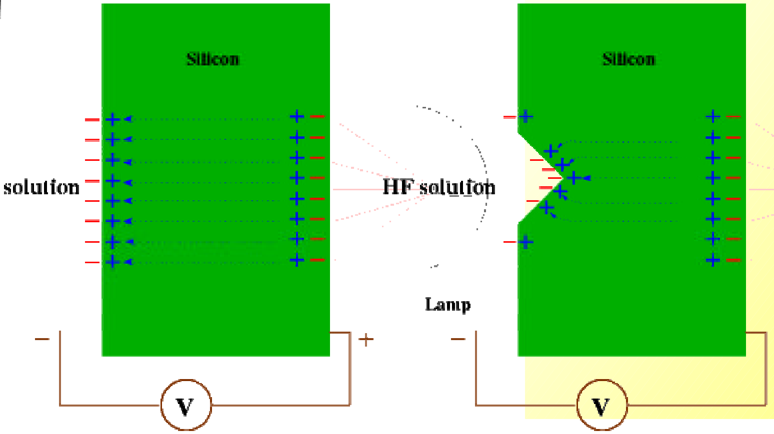
- Expect ~100:1 aspect ratio
- Control voltage → controls etch current density
- ~9 hours to reach ~200mm
- PEC reaction only in Si

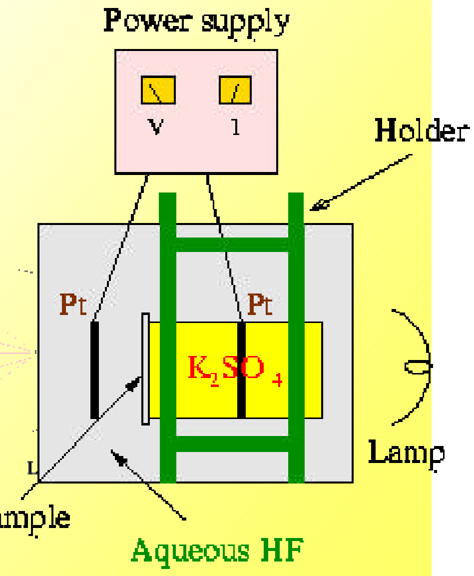
$Si + 2\,HF + 2\,h^{+} \rightarrow SiF_2 + 2\,H^{+}$

$2\,SiF_2 \rightarrow Si + SiF_4$

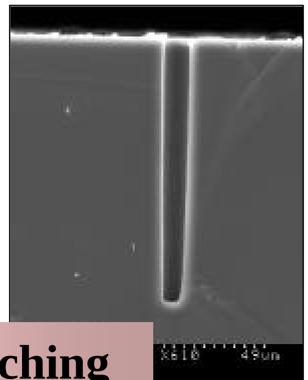
$SiF_4 + 2\,HF \rightarrow H_2SiF_6$

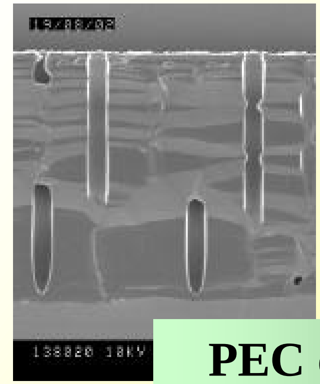






Manufacture of 3D detectors



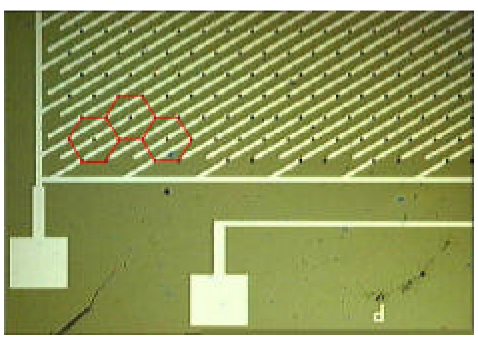


Plasma etching

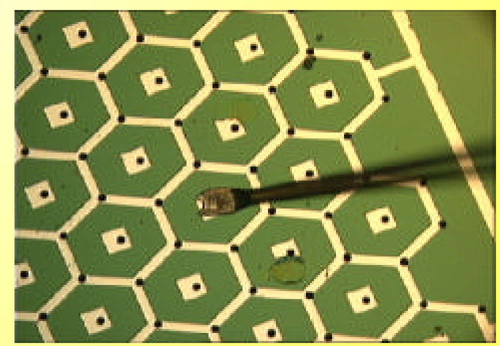
Laser ablation

PEC etching

Cross-section SEMs of 3D pores made by the three methods

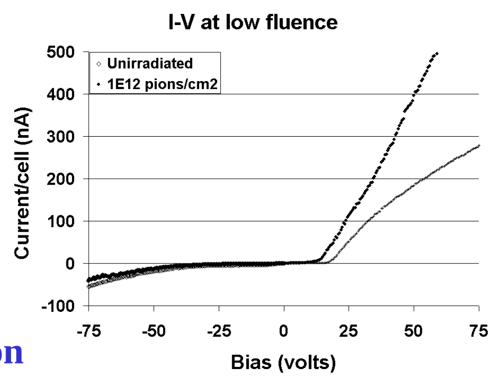


3D hexagonal geometry connected in strip and pixel configurations

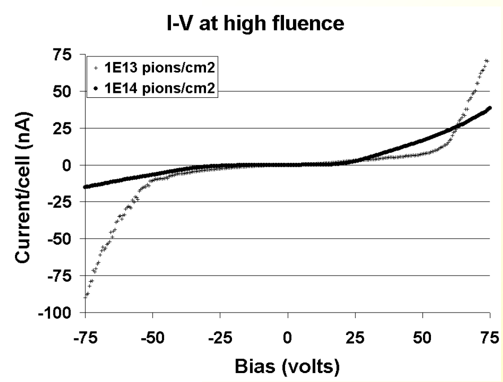


Irradiated 3D detectors

Irradiation 10^{12}, 10^{13}, 10^{14} π/cm^2 at 300 MeV/c pion beam PSI Villigen



a)

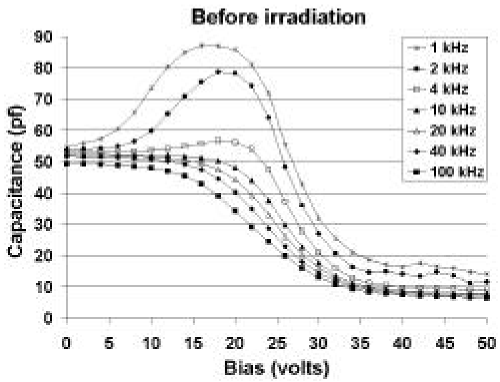


b)

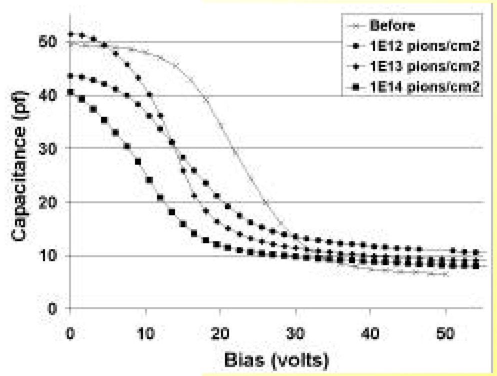
I-V before and after irradiation

85µm pore spacing, 200µm silicon

Full depletion by 50V even after 10^{14} p/cm^2



c)

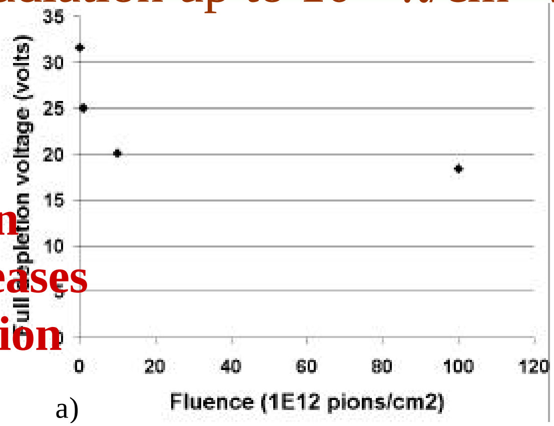


d)

C-V before and after irradiation

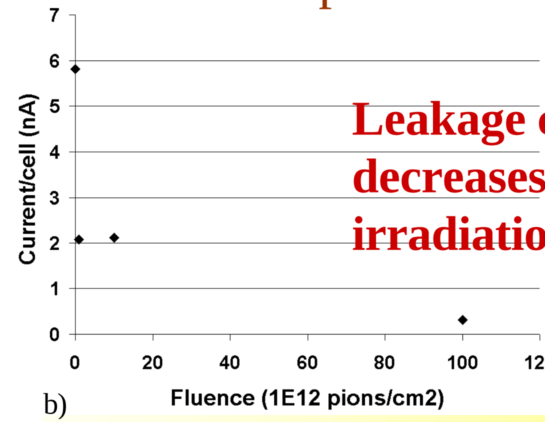
Irradiated 3D detectors

Irradiation up to 10^{14} π/cm^2 with 300 MeV/c pion beam



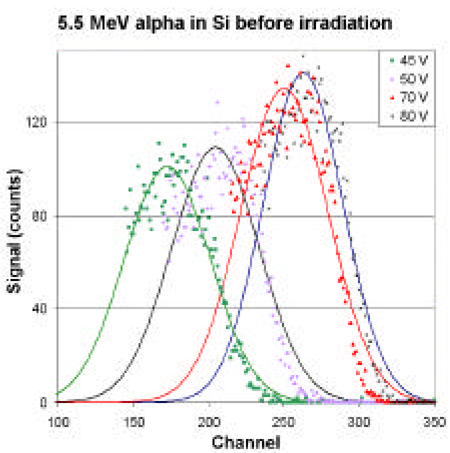
a)

Full depletion voltage decreases with irradiation



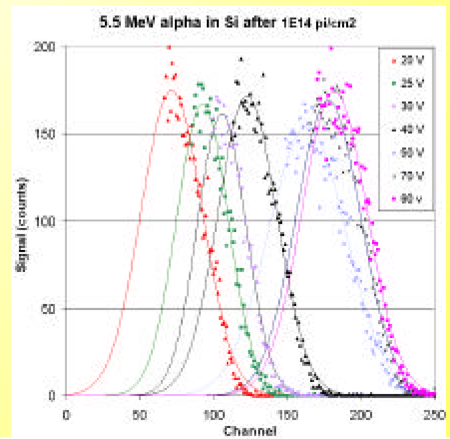
b)

Leakage current decreases with irradiation



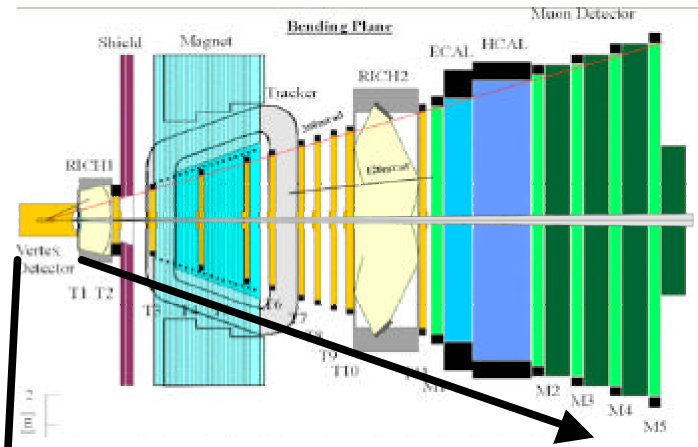
5.48 MeV a **pulse height spectra before (←) and after (→) 10^{14} p/cm^2 irradiation**

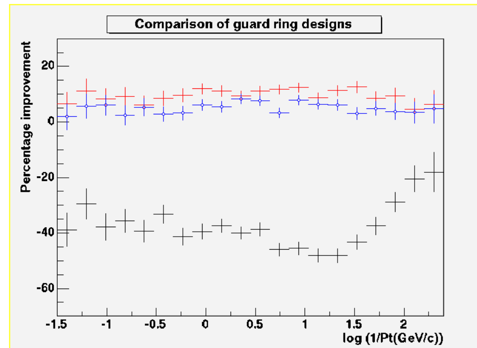
CCE: before ~ 60%
after ~ 45%



3D detector for LHCb / Velo

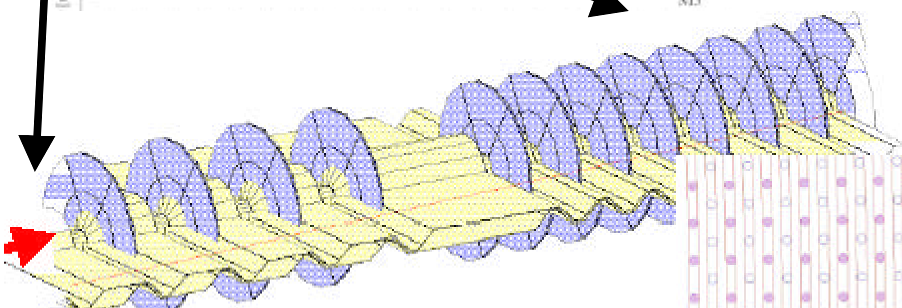
3D to improve impact parameter resolution and lifetime



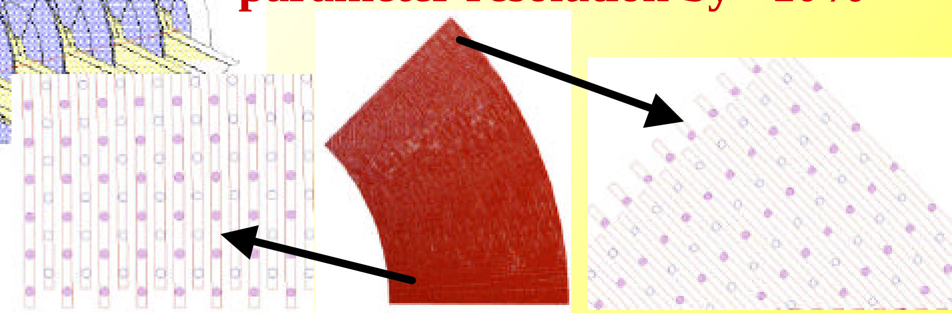


Gaudi/Brunel simulation of guard ring width

- **Silicon is 8mm from beamline**
- **Reduction by 1mm improves impact parameter resolution by >10%**



LHCb vertex locator



3D design for Velo

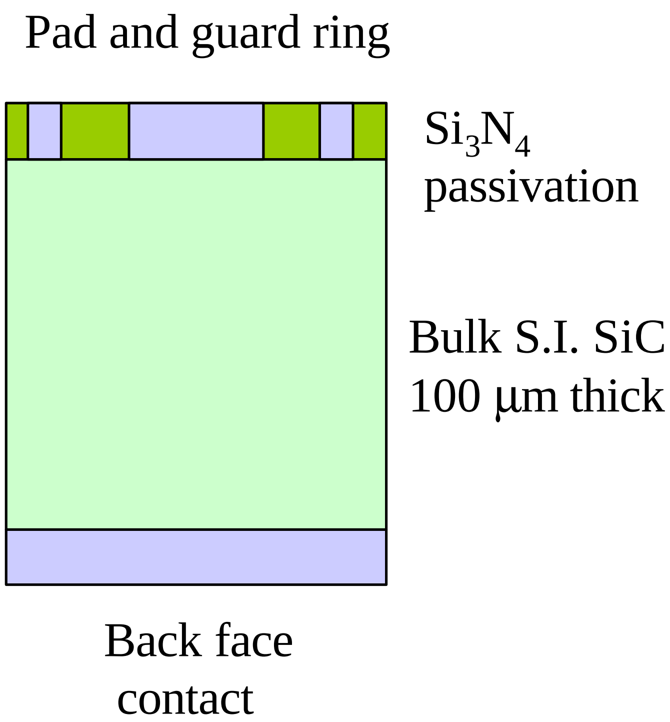
Radiation hard particle tracking II: Silicon carbide detectors

Ideal detector medium

- High purity to enhance CCE – Ge is purest material, owing to low melting point 960°C, background level ~10^9 cm^{-3}
- Large bandgap to suppressed thermal carriers [~$T^{3/2}\exp(-E_g/2kT)$] & defect recombination/generation current [~ $np - n_i^2$] – SiC is ~3.3eV, D is ~5.5 eV
- High μ_n, μ_h v_{sat} give lower τ_{coll} – GaAs good, SiC & D have higher v_{sat}
- Low Z number to lessen radiation losses – SiC & D both better than Si, GaAs
- Low e-h excitation energy to enhance signal – D bad (15 eV), SiC (9.0 eV) like Si (3.6 eV)
- Low e to reduce capacitance – D (5.7) & SiC (9.7) better than Si (11.9)
- High bond strength to reduce defect production – SiC and D both good
- High thermal conductivity to dissipate power – SiC & D are excellent

SiC detectors

Fabricated on bulk semi-insulating 4H-SiC from Cree

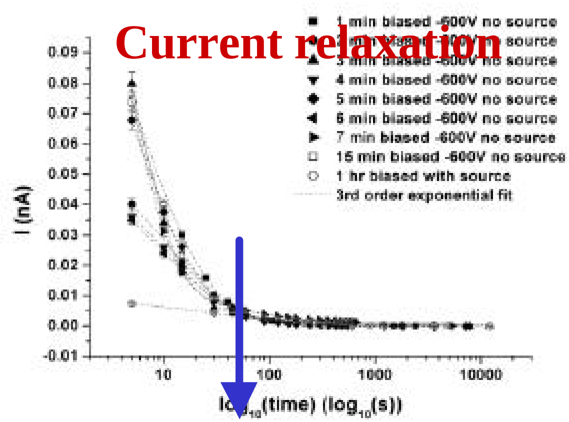


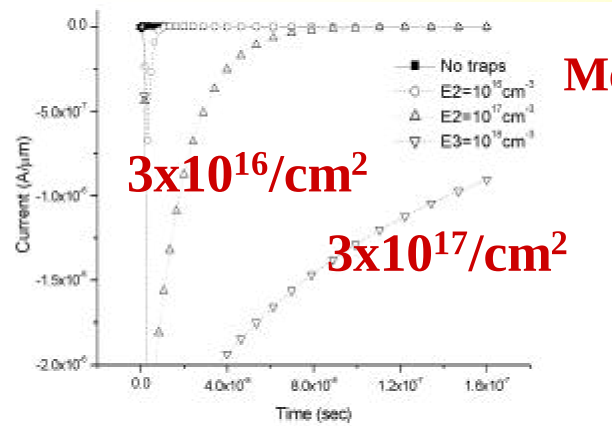
- **Schottky barrier diode on 4H semi-insulating SiC**
- **Pad and guard ring 100nm Ti**
- **Back contact 100nm Ni**
- **200 nm Si_3N_4 for surface passivation**

Effect of defects in Cree 4H-SiC

Simulations suggest degradation only at fluences $>10^{16}/cm^2$

Current relaxation



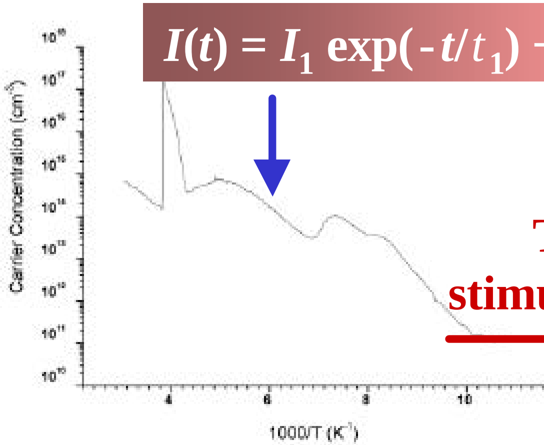


Medici

$3x10^{16}/cm^2$

$3x10^{17}/cm^2$

$$I(t) = I_1 \exp(-t/t_1) + I_2 \exp(-t/t_2) + I_3 \exp(-t/t_3)\ ,\ (c^2 \text{ » } 0.99)$$



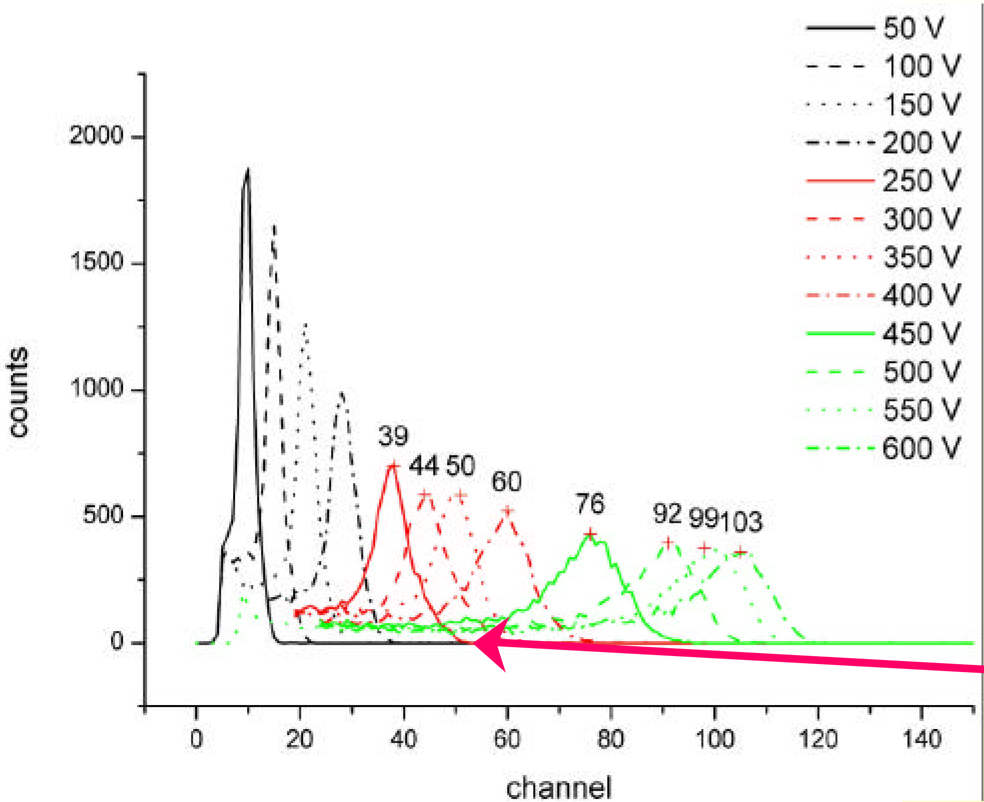
Thermally stimulated current

T (K)	Ea (eV)	Identification
118	0.32	Localised dislocation Sghaier et al
135	0.39	Localised dislocation Sghaier et al
200	0.63	Hexagonal lattice point C vacancy Bechstedt et al
260	0.92	Vanadium activation Reshanov et al

Trap identification

Pre-irradiation spectra

100μm thick bulk SiC 0.5mm diameter diode

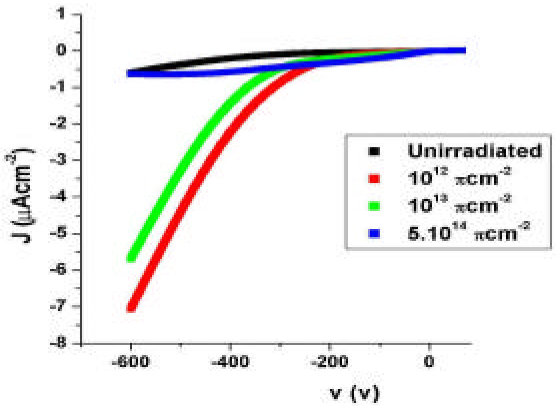


- **Spectra taken for 5.48 MeV Am^{241}** a **particles**
- **SRIM: 5.48 MeV** a **range in SiC is ~18**m**m**
- **Max CCE 60% at -600V**

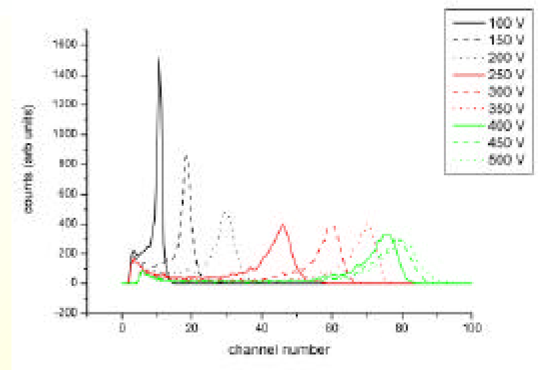
Large low energy tail

4H-SiC detectors after irradiation

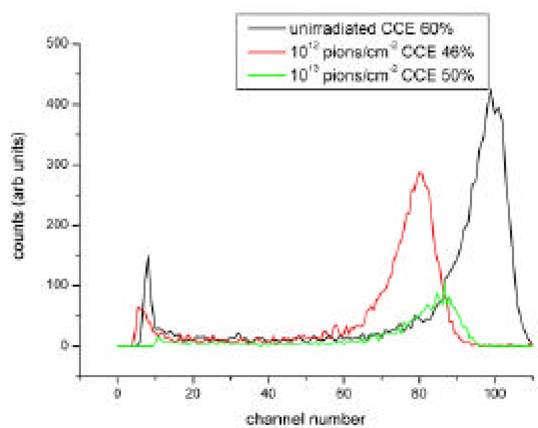
I-V and α spectra



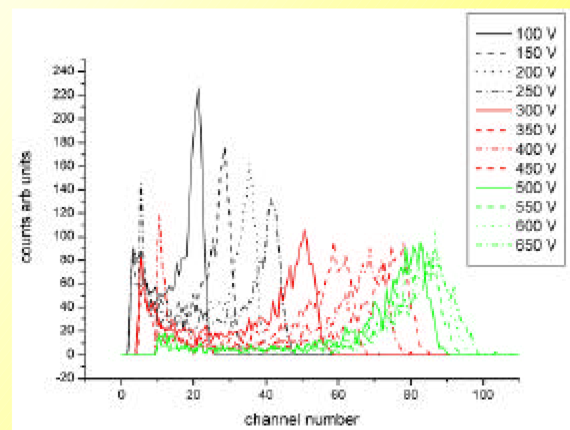
I-V with irradiation 10^{12}, 10^{13}, $>10^{14}$ p/cm^2



10^{12} p/cm^2



CCE: 60% → 50% with 10^{13} p/cm^2



10^{13} p/cm^2

Italian groups have seen 100% CCE in epi-SiC ~20mm thick

Photon counting for X-ray imaging – the Medipix

X-ray imaging technologies

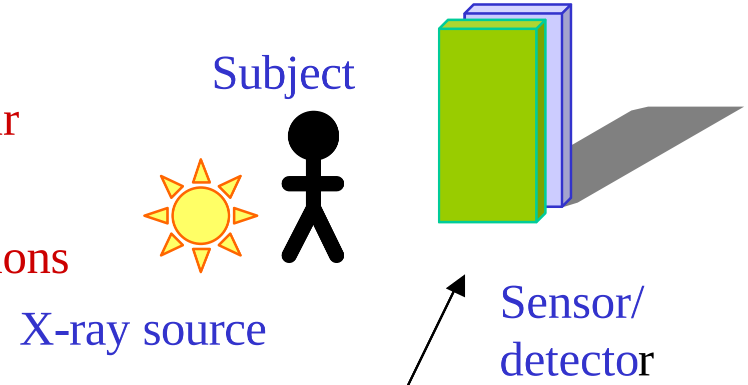
Film, CCD/TFT, hybrid pixel

Applications: dentistry, mammography, cardiography, etc

Film: simple, established

Digital:

- less film processing, archiving, labour
- increased speed, patient throughput
- image processing, advanced applications
- *reduced dose to patients*



Digital technologies

CCD: light guides to chips

TFT: flat panel

hybrid: tiled panel

Film	Emulsion, phosphor
CCD/TFT	CsI, GdOS, CZT - light conversion
hybrid pixel	Si,GaAs,CZT - charge conversion

Digital CCD / TFT technology

Dental CCD, TFT flat panel

CCD: High resolution ~10µm (>10 lp/mm), needs converter (GdO), fogging due to dark currents, blooming due to well capacity, large areas need light guides, additional parts increase noise

TFT: Large area cheaply, medium resolution ~100µm (~5 lp/mm), needs converter (CsI)

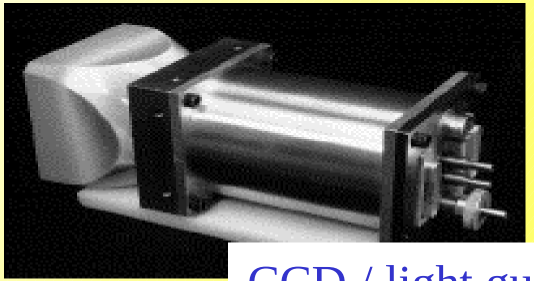
~1/5 dose of film, depending on noise/contrast

CCD / dental

TFT flat panel

mammogram

cardiogram



CCD / light guide

Technology enhancement

•CCD/TFT technology relatively straightforward to implement - pixels are relatively simple; permit high resolution or large area integration of image

•Improvements in device miniaturisation and multi-chip module technology now mean that pixels may be made small and also ‘smart’

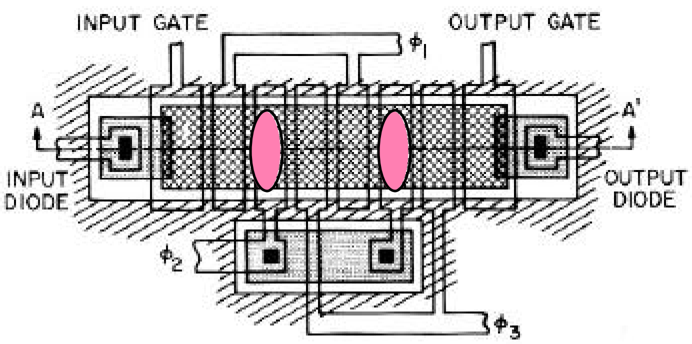
•So design chip that will count photons of a particular energy

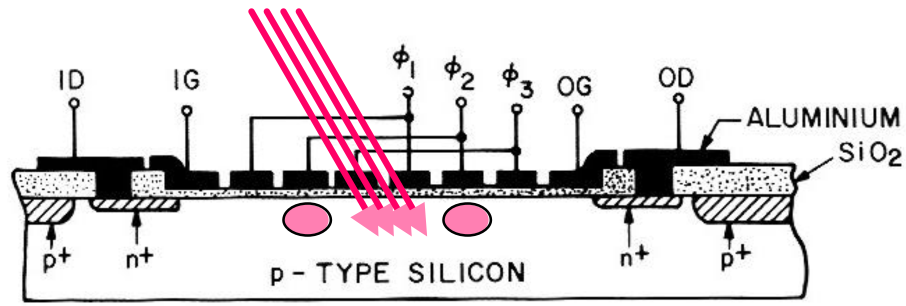
- Will be linear over the dynamic range of the counter
- Ability to count small numbers of photons means potentially reducing dose down to smallest limit possible
- Detecting photon energy (harder with CCD / TFT) will offer potential improvements to image quality, so better diagnosis

Charge integration vs photon counting

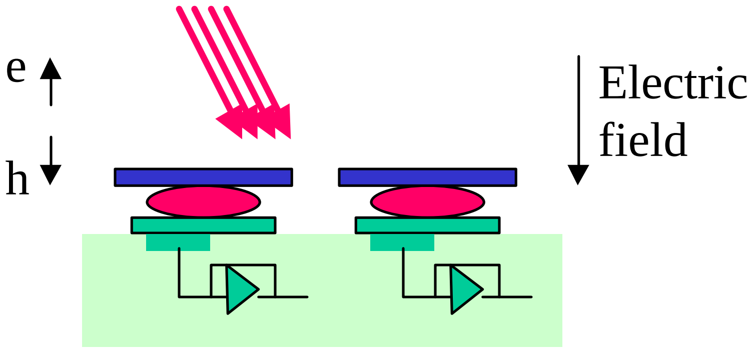
Pixel functionality for dose reduction

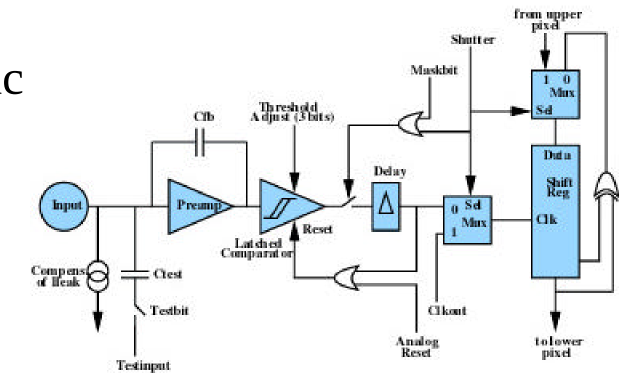
CCD system: charge integration, affected by leakage currents





Photon counting: count individual incoming photon, no leakage effects



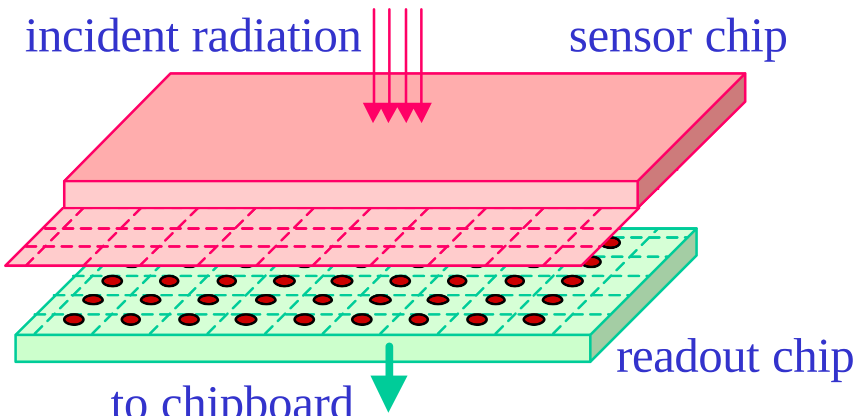


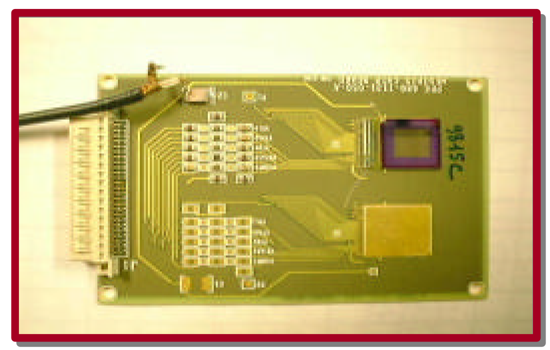
Hybrid pixel technology

Development of photon counting from particle physics applications

Increased pixel functionality (CERN Microelectronics):

	Year	Array size	Cell size (mm´mm)	Trans/cell
LAA	1988	9×12	200×200	40
OmegaD	1991	16×63	75×500	81
Omega2	1993	16×63	75×500	81
Omega3/LHC1	1995	16×27	50×500	395
Medipix1	1997	64×64	170×170	400
Medipix2	2002	256×256	55×55	502





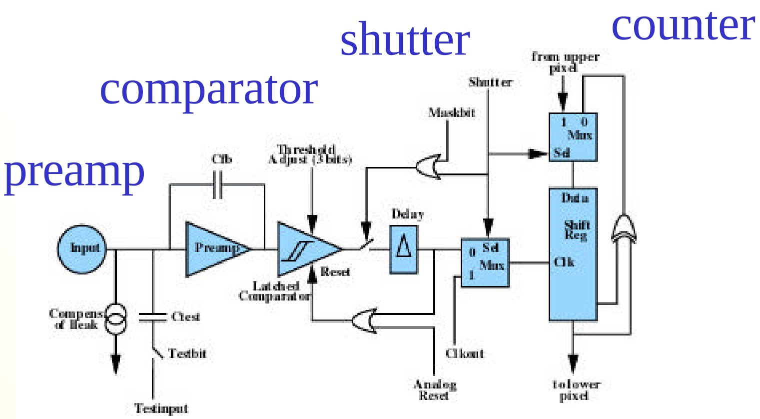
Medipix1 on chipboard

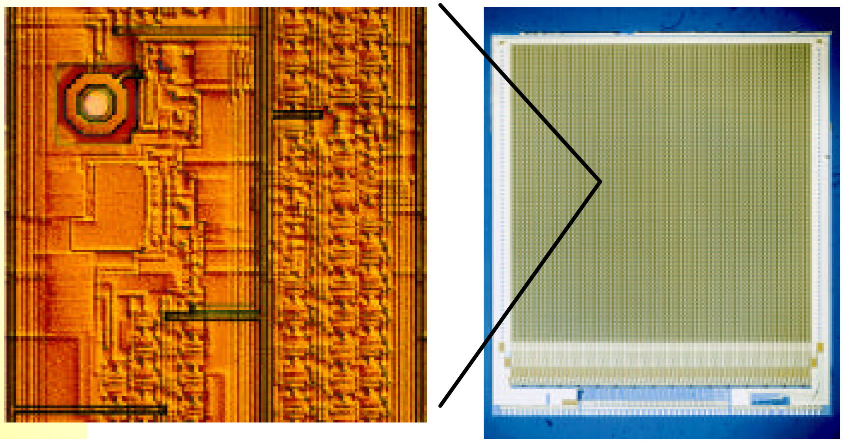
Medipix1

Developed at CERN Microelectronics

Properties:

- 1 μm gate length SACMOS
- 170×170 μm² pixels
- 64×64 pixel array
- sensitive to positive charge only
- column-wise leakage compensation 10nA max
- single discriminator (energy threshold) with 3-bit tune
- 15 bit counter
- readout time 384 μs

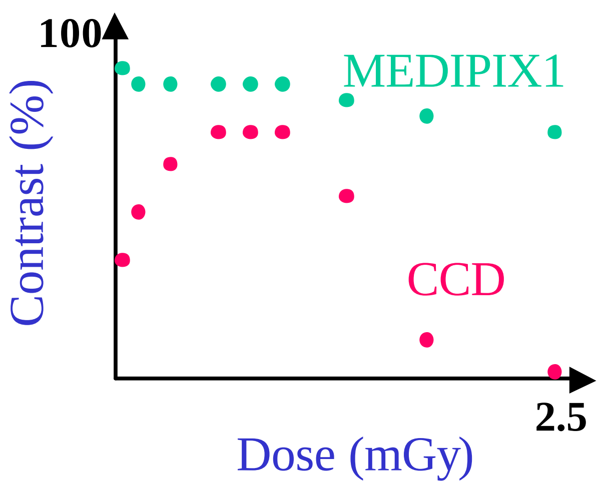




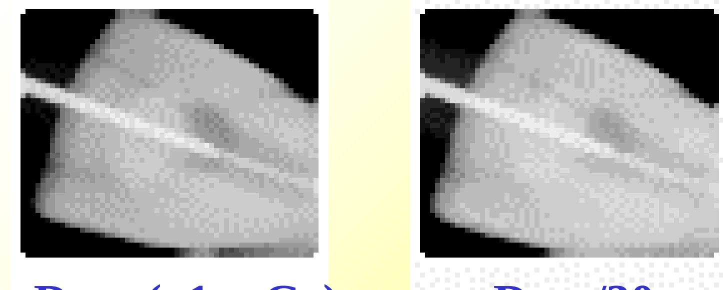
Dose reduction with Medipix1

Compare against CCD / dental gun (~30 keV X-ray photons)

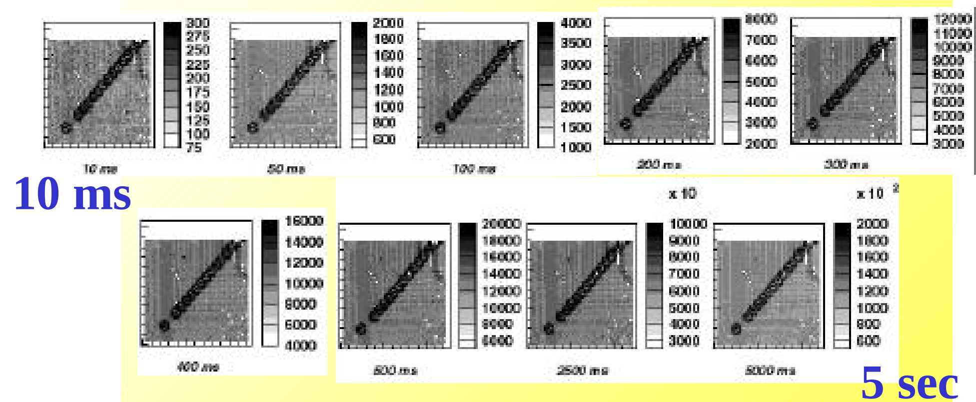
- Sens-A-Ray dental CCD from Regam Medical (Sweden)
- Contrast and noise performance of Medipix1 is much better, with dose reductions of >30 possible



(Tooth images courtesy B Mikulec, CERN)

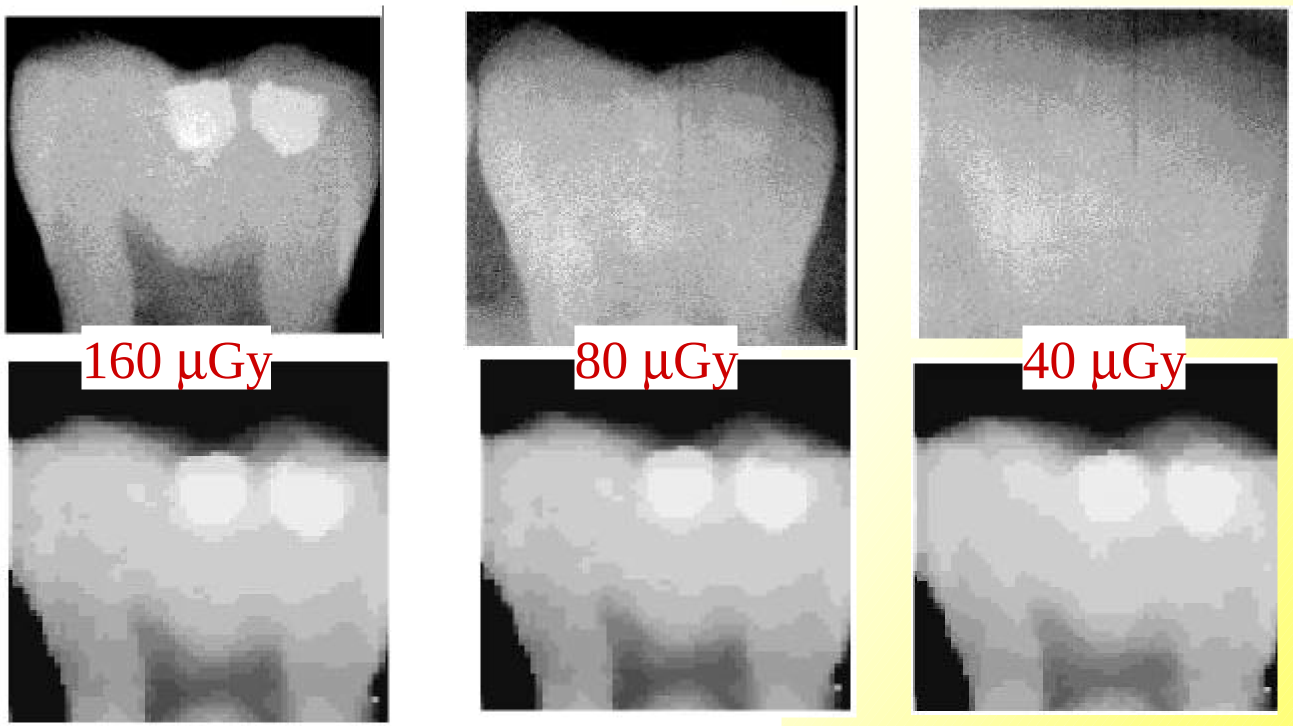


Dose (~1 mGy)　　Dose/30



Comparing CCD with Medipix1

Sens-A-Ray (Regam Medical)



Medipix1

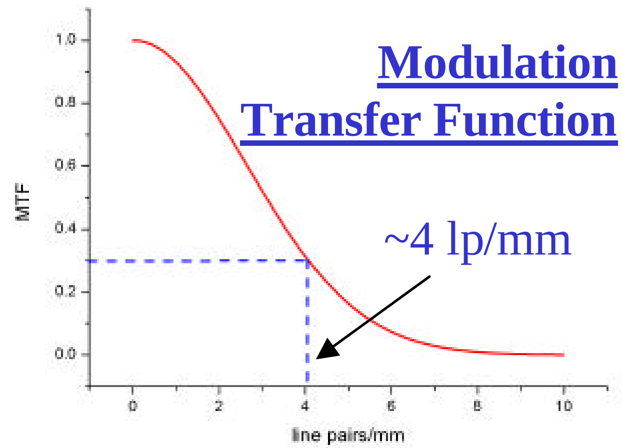
Spatial resolution of Medipix1

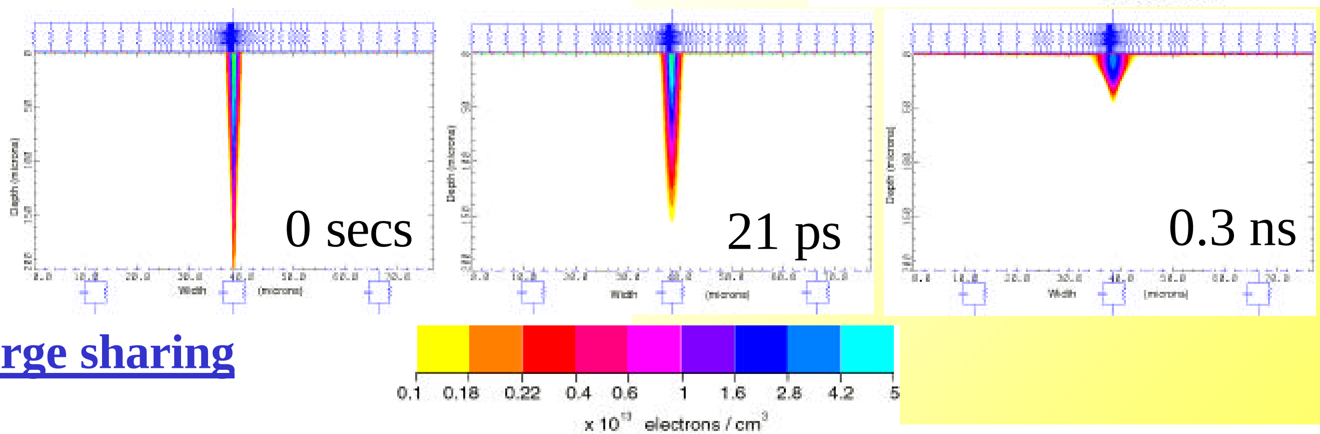
Pixel size is not always image resolution

•Image resolution affected by contrast, noise and detector geometry

•MTF = Fourier transform of Line Spread Function (measured by exposing a slit)

•Charge sharing influences counts at small pixel size





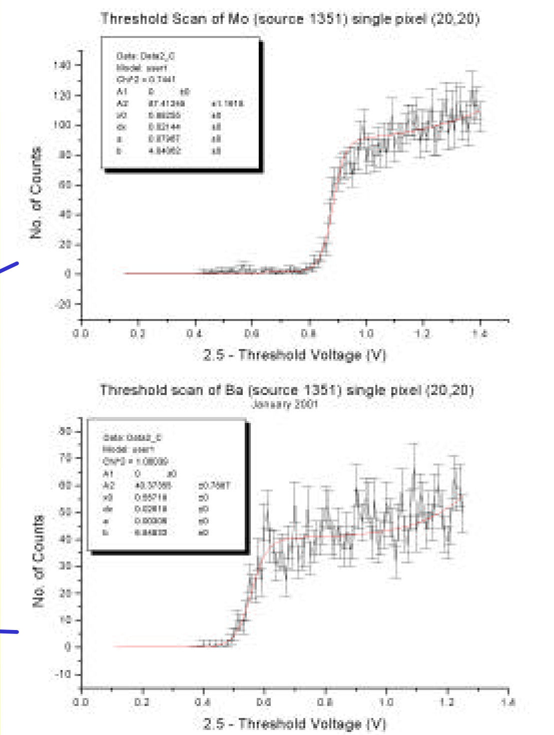
Charge sharing

Energy filtering in Medipix1

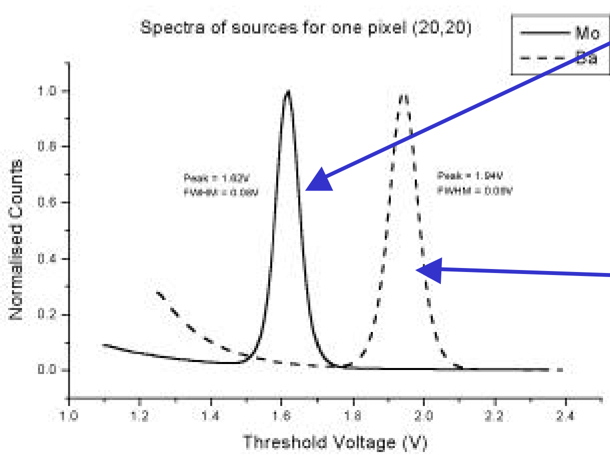
Comparator threshold allows filtering of image in energy

- *Not easy in CCD/TFT technology*
- Incident photon energy gives *N* e-h pairs (typically few 1000s e^-)
- Comparator permits counting only if *N* exceeds threshold (>2000 e^-, noise ~250 e^-)
- Allows eg Compton background to be suppressed, improving image

Mo source (17.4 keV)



Ba source (32.1 keV)



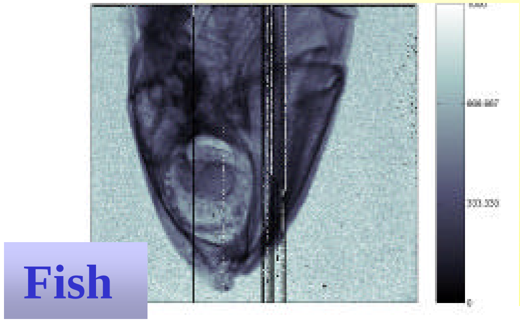
Medipix2

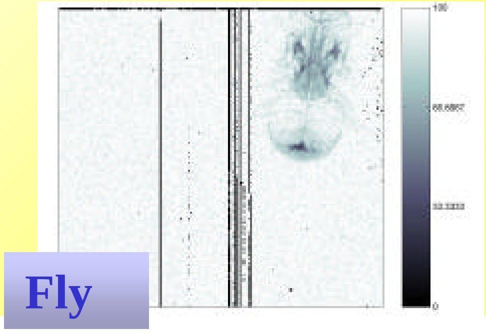
First batch of chips under test

Properties:

- To permit ~10 lp/mm, 55×55 μm^2 pixels
- To allow sufficient functionality within pixel, 0.25 μm gate length CMOS
- Area coverage 256×256 array, ~1.4×1.4 cm^2 active area
- To permit Si, GaAs, CZT etc, electron and hole collection
- To equalise spatial inhomogeneities in leakage, pixel-wise compensation between +10 nA and -4 nA
- To permit energy windowing, twin adjustable thresholds
- Smaller photon flux per pixel than Medipix1, so 13-bit counter with overflow
- To allow large area coverage, 3-side buttable

First 'real' images →





Smart pixel detectors for artificial vision to repair blindness

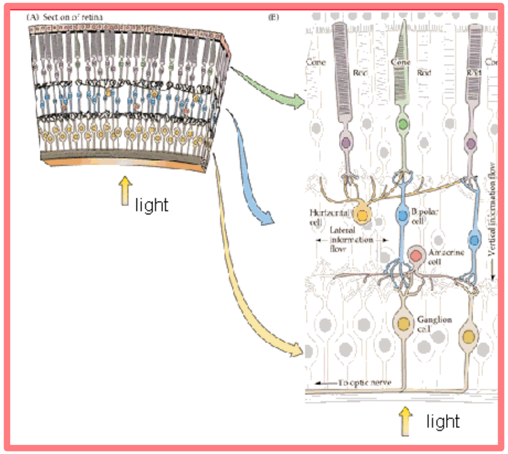
Retinal degeneration and blindness

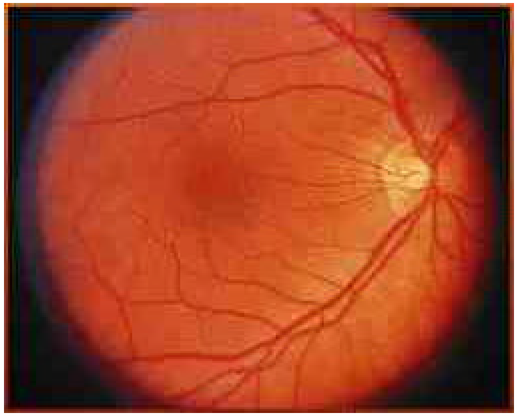
- **Leading causes of blindness in West (~8% of population):**

  Age related macular degeneration (affects rods – central vision)

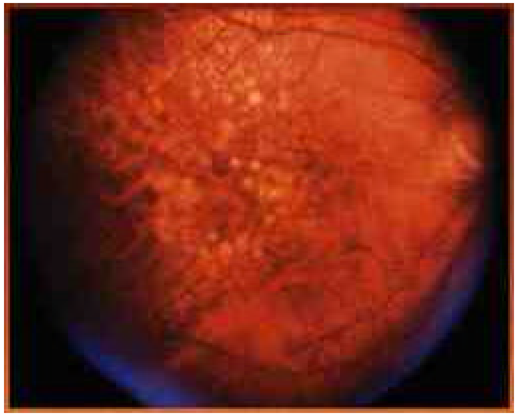
  Retinitis pigmentosa (affects cones – peripheral vision)

- **Ganglion cells (connect to optic nerve) stay intact initially**





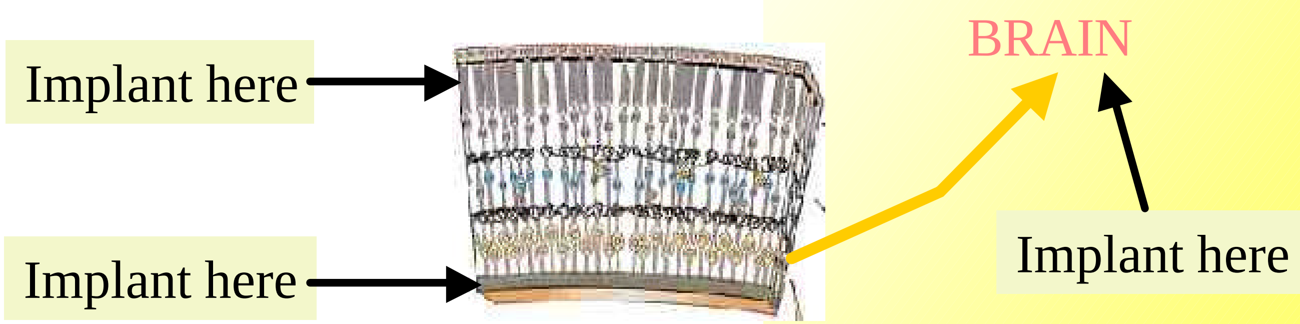
healthy



degenerated

Artificial vision

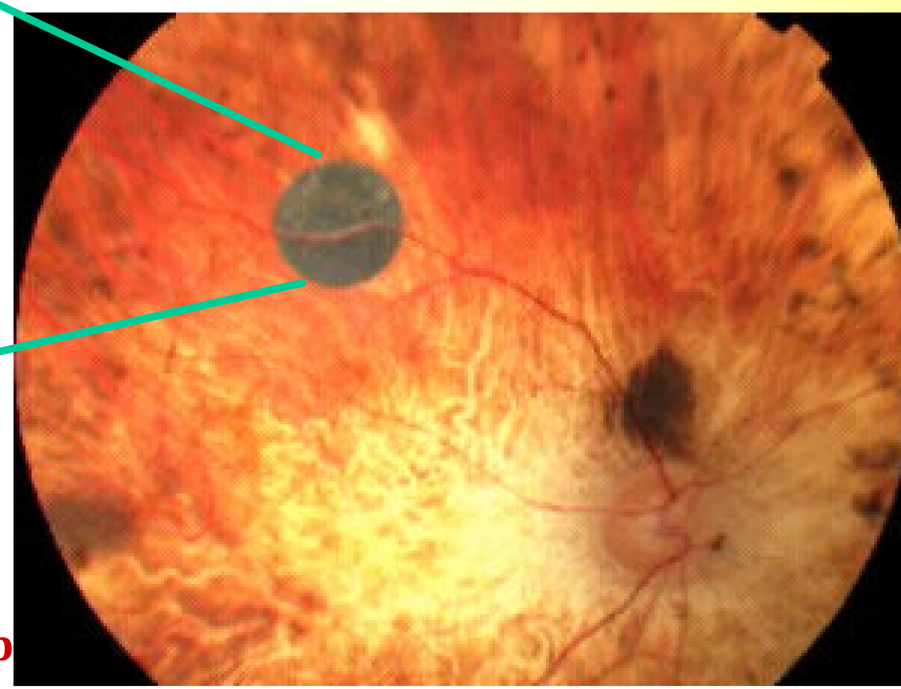
- For stimulation of retinal ganglions:
  - Make retinal implant to replace lost rods and cones - either photodiode arrays (Tubingen) or ‘smart’ arrays hooked to computer (Baltimore)
  - Make implant to sit on ganglion surface, excited by laser (MIT, Bonn)
- For damaged nerve fibres:
  - Connect video directly to visual receptors in brain via a pin-grid array cortical implant (Utah)



Artificial retina chips

Clinical trials by Optobionics Corporation (USA)

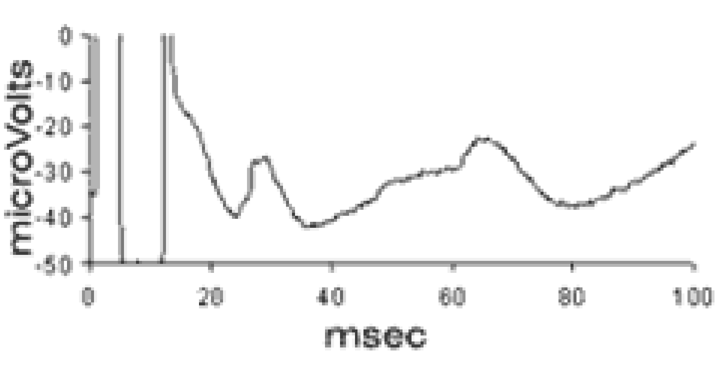
Fabricated chip, self-powered using solar cells

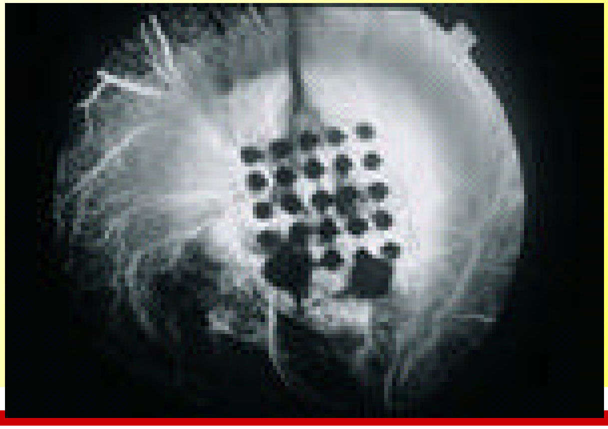


Implanted chip

Artificial retina chips

Patient trials at Johns Hopkins Hospital, Baltimore (USA)

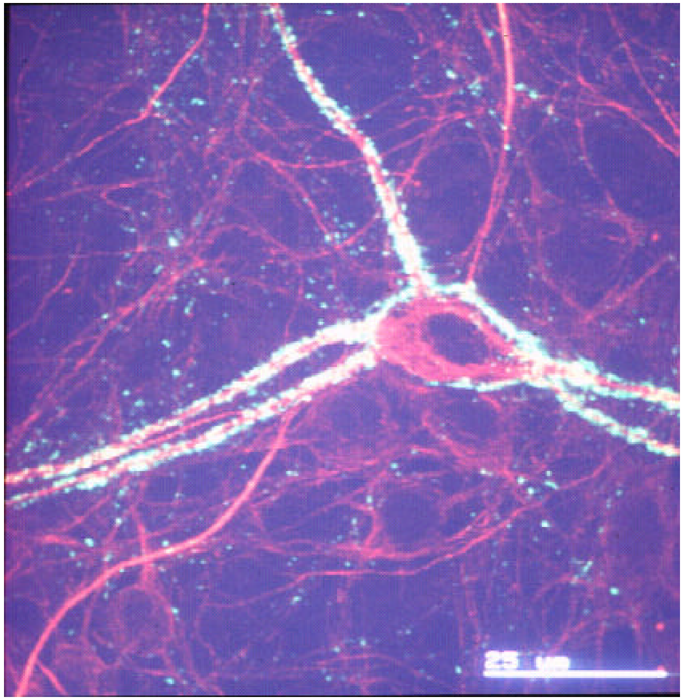




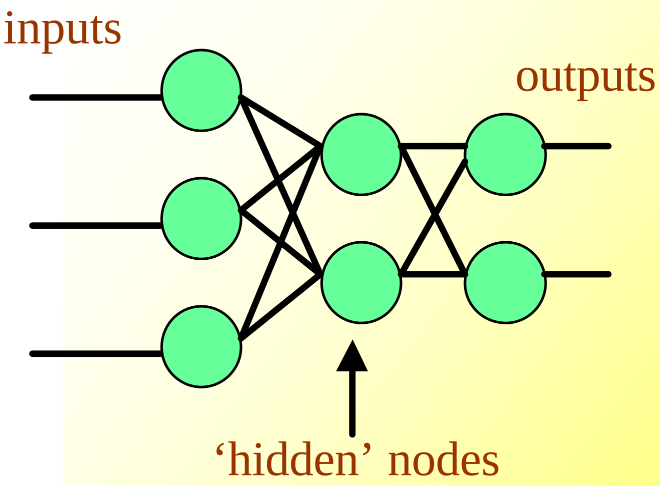
Chip 'hardwired' to outside world

Artificial neural networks

Emulating biological neural networks by connectionism



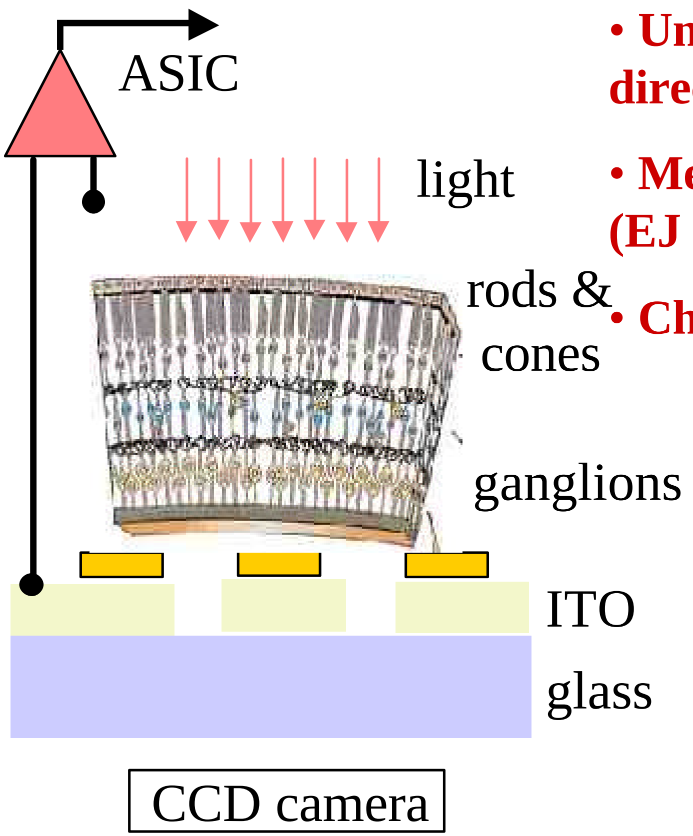
Part of biological neural network



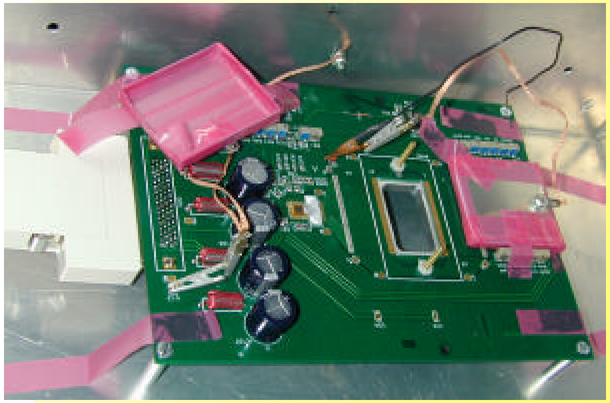
- bPhysicist’s neuron: McCulloch & Pitts (1943)
- 3-layer/weighted sum: Rumelhart & McClelland (1986)

Retinal readout board

Designed at UC Santa Cruz (A Litke)



- **Understand the functioning of the retina by direct measurement of retinal activity**
- **Measurements at Salk Institute, San Diego (EJ Chichilnisky)**
- **Chip design from Krakow (W Dabrowski)**

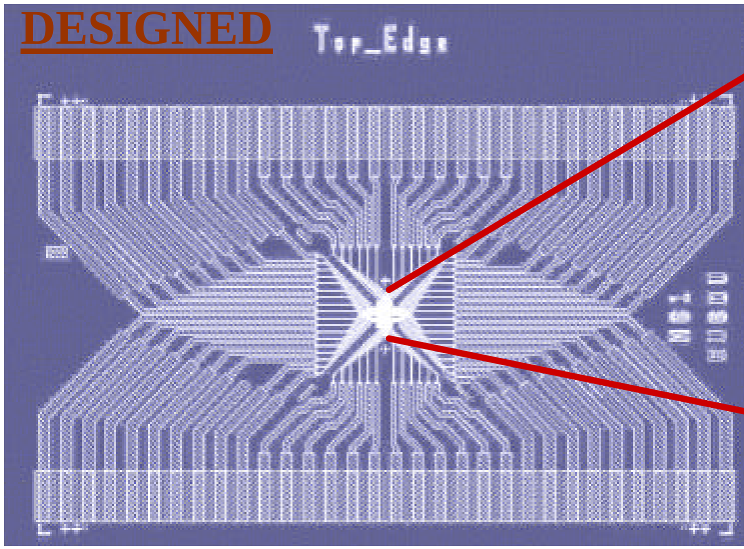


64 electrode system

61 electrode array

Fabricated using photolithography and dry-etch

DESIGNED



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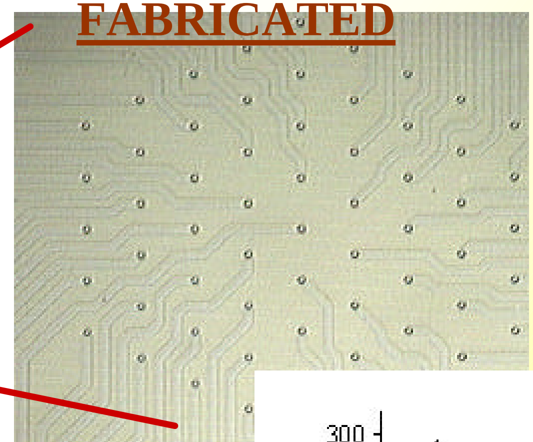
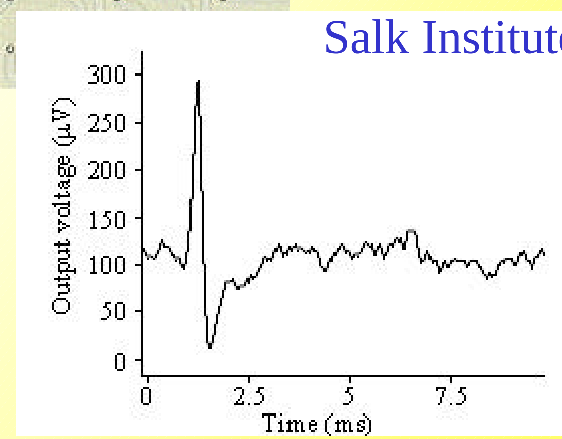
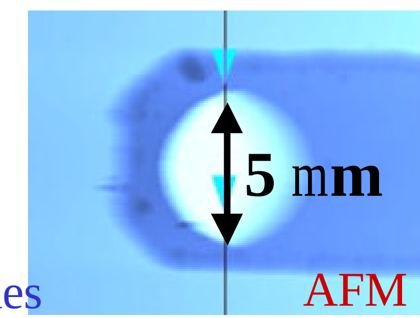


Measurements at Salk Institute



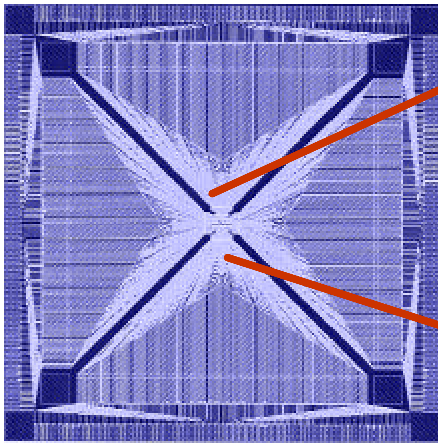
Platinised electrodes



AFM scan of single electrode

519 electrode array

Fabricated using multi-layer masking and e-beam



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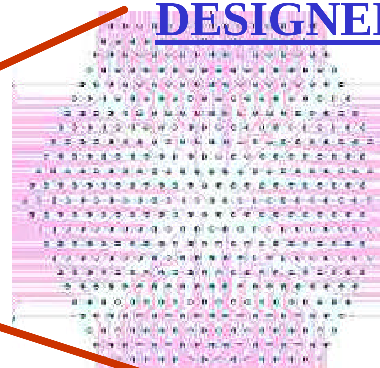

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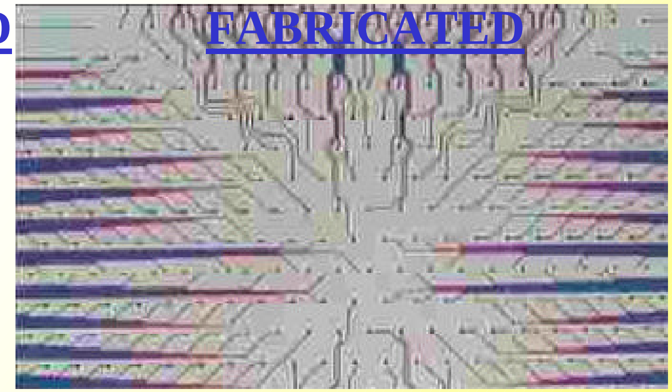
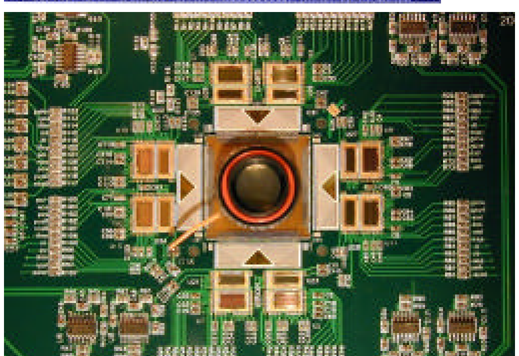
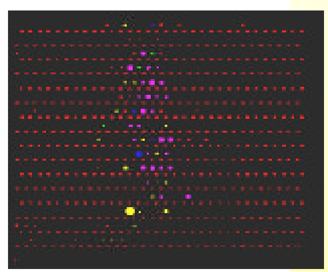
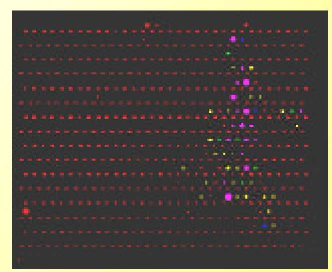


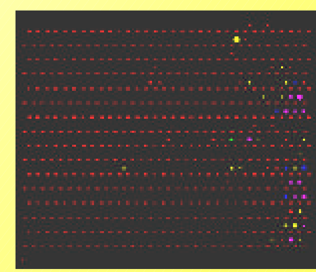


Santa Cruz board at Salk

Salk movie using 512 readout system

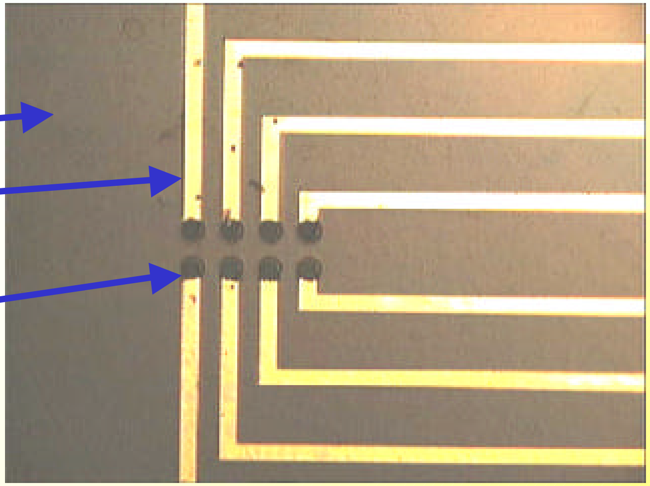


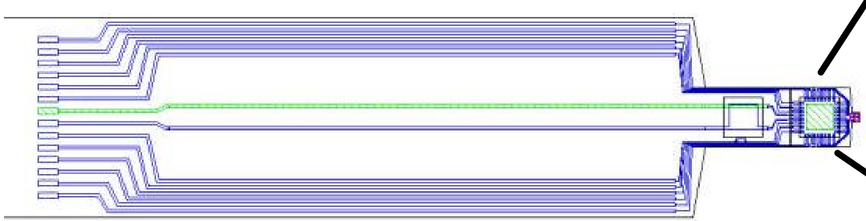


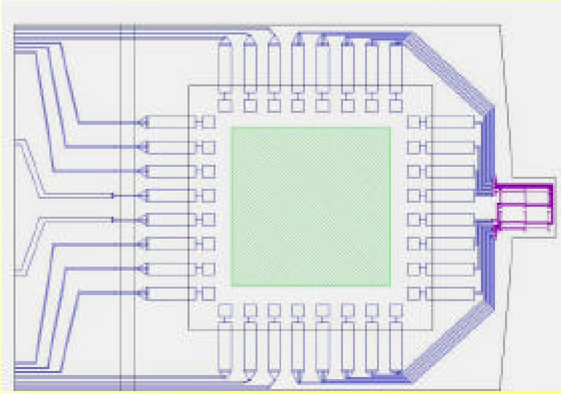


Prototype retinal implants

- Initially an 8-electrode array fabricated on a biocompatible substrate
- Polyimide substrate (Kapton)
- Gold wire connections
  - Fabricated down to 10µm wires
  - Should be possible to go smaller
- Platinum electrodes
  - 25 µm diameter
  - Biological signals detected
  - Electrode characteristics well behaved
- CAD designs for test implant







Neural net retina chip

Designed as three-layer feedforward neural network

LAYER 1-2

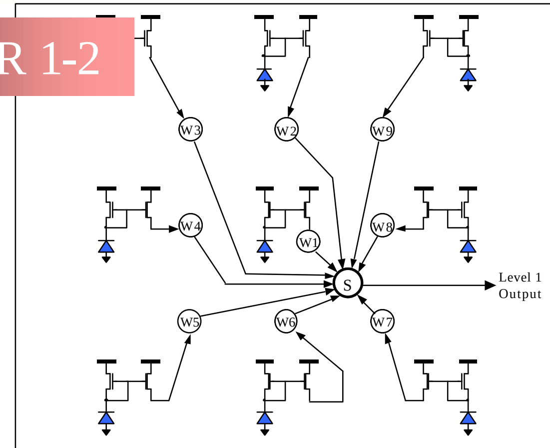
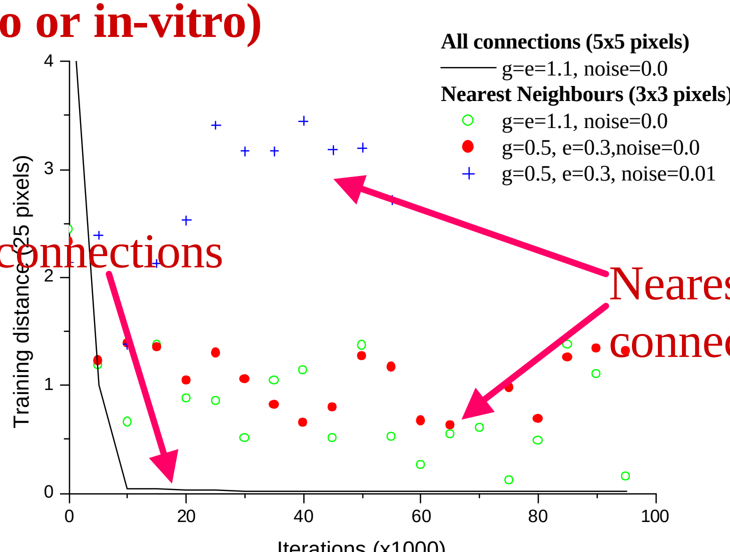


Figure 3. Neural Network Level 1.

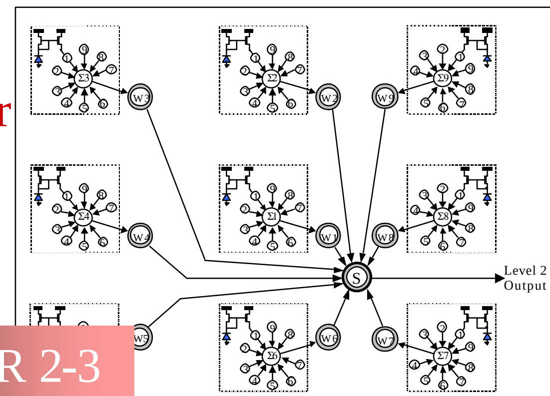
- **Design retina chip with programmable weights (10x10 monolithic active pixel sensor – RAL)**
- **Train from retinal readout measurements (in-vivo or in-vitro)**



All connections

Nearest neighbour connections

network convergence for 5x5 array



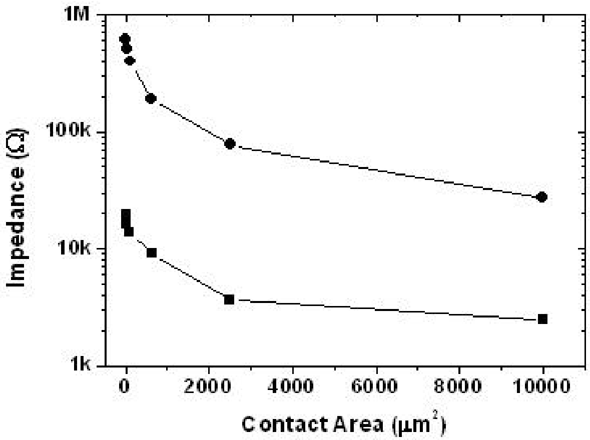
LAYER 2-3

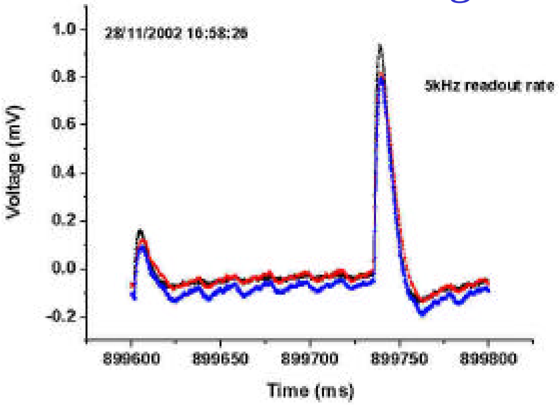
Figure 4. Neural Network Level 2.

Retinal implant electrodes – initial tests

- Platinisation required to reduce electrode impedance
- Initial implant tests with cultured neural & heart cells → measured signals
- Next step incorporate retina chip (RAL designers) + power

Heart cell movie and signal





Summary

- 3D detectors show much promise – only few groups world-wide making them.
- SiC shows initial promise as radiation hard material - growing interest.
- Photon counting technology used in particle tracking, now being exploited for X-ray imaging
- Imaging and DAQ techniques from high energy physics being used to design a neural network retina chip / implant for repairing certain types of blindness

Acknowledgements

Including (not exhaustive list):

3D/SiC – M Moll, C Joram, M Glaser (CERN), K Gabathuler (PSI); C Parkes (Glasgow), D Jones, D Jaroszinski (Strathclyde); S Parker (Berkeley), C da Via (Brunel); V Kazukauskas, J Vaitkus (Vilnius); HE Nielson (Mid-Sweden), B Svensenn (Oslo), I Pintellie (Hamburg), B Jones (Exeter), M Bruzzi (Florence); L Lea (Surface Technology Systems); J Linross, X Llalport (KTH)

Medipix – M Campbell, L Tlustos, B Mikulec (CERN); Medipix collaboration (CERN, Naples, Pisa, Calgiari, Frieburg, Mid-Sweden, NIKHEF, Prague, MRC Cambridge, CEA Saclay, ESRF Grenoble, Panalytical, Glasgow)

Retinal – CDWilkinson, AJ Curtis, A Beattie (EE/IBLS – Cell Engineering), J Morrison (IBLS – retinal surgery); A Litke, EJ Chichilnisky, W Dabrowski (retinal readout); M French, M Prydderch, R Turchetta, J Crooks (RAL – neural net retina chip design); JIB Wilson, M Lal (HW/NPL – solar cells); M Cooke (Oxford Plasma Technology)